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The Performance of Hydrocarbon Fuels with H_2O_2 in a Uni-element Combustor

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Abstract

A team from Sierra Engineering Inc. (Sierra), AFRL, and Northrop Grumman Corporation (NGC, formally TRW) tested several different hydrocarbon fuels in a uni-element, 1300 pound thrust hydrogen peroxide/ hydrocarbon rocket combustor. Tests were conducted with a variety of hydrocarbon fuels, including JP-8, RP-1, JP-10, toluene, quadricyclane and turpentine, as well as several mixtures of these fuels. The combustor used decomposed 90% hydrogen peroxide as the oxidizer. The water-cooled combustion chamber included significant fuel film cooling, with the overall mixture ratio (MR) ranging from 3.75 to 7.4. Testing was conducted at a chamber pressure of approximately 800 psia. Figures of merit presented in this paper include characteristic velocity (ηC^*) and energy release efficiencies (ERE). Agreement was generally excellent, with ηC^* and ERE agreeing to within 1%. The experimental performance results were compared with theoretical performance computations. The exhaust plume was monitored during the tests with an infrared spectrometer. Results are shown for integrated band intensities, demonstrating the sensitivity of the plume radiance to variation in combustor operating conditions. In several instances, the variations of the plume intensity could be correlated with events occurring within the combustion chamber. However, the plume measurement was more sensitive than the direct measurements of chamber operating condition (such as pressure and temperature measurements).

Introduction

Because they represent the potential for higher performance or increased coking onset limits, there is strong interest in exploring the use of alternative and advanced hydrocarbon fuels for use in next generation liquid rocket engine design. Over the last several years, several of these alternative hydrocarbon molecules have shown great promise for use as either a fuel or an additive to be blended with traditional hydrocarbon fuels. Few of these molecules have been extensively tested to determine whether the theoretical performance increase is attainable in a rocket engine. This study documents performance data acquired from combusting several of these alternative hydrocarbon fuels and fuel blends in a small hydrocarbon/hydrogen peroxide bi-propellant combustor. These fuels were tested in a 1300 pound thrust combustor at AFRL Edwards test site, and performance data from those tests were obtained. The testing team included personnel from Sierra, AFRL, and NGC.

The testing in this project supported the development of the Liquid Propellant Booster Target System (LBTS) program run by the Missile Defense Agency's (MDA) Missile Defense Targets Joint Project Office. The end product of the LBTS program is a low-cost liquid fueled missile target for use by missile defense programs. MDA selected hydrogen peroxide and hydrocarbon propellants for use in this system. NGC is currently funded to develop and fly a prototype LBTS. Sierra, with help

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from NGC, created and fired this subscale hydrogen peroxide / hydrocarbon combustor as part of an MDA Small Business Innovative Research (SBIR) contract.

In addition to the traditional measures of performance (i.e., thrust, chamber pressure, etc.), a Bomem MR200 Fourier transform infrared radiation (FTIR) spectrometer was used to monitor exhaust plume radiation intensity. Several interesting observations were made regarding the spectrometer's ability to sense variation in engine operation.

This paper will describe the engine performance data acquired during this testing to give a preliminary indication of the potential of some of these hydrocarbon fuels for use as a rocket propellant. In addition, data will be presented showing the potential of engine plume measurements to yield information regarding rocket engine performance.

Hardware Description

The test hardware, shown in Figure 1, used a screen catalyst bed to decompose 90% concentration hydrogen peroxide into a hot, oxygen-rich steam. The decomposition products were subsequently combusted with a hydrocarbon fuel to produce approximately 1300 pounds of thrust at a chamber pressure of 900 psia. The nominal hardware design conditions, assuming 95% ηC^*, are listed in Table 1.

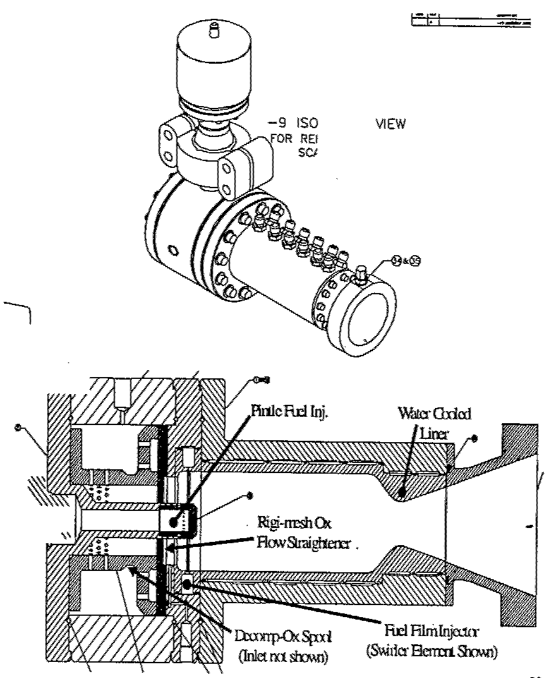

Figure 1. Layout of Signature Tailoring H_2O_2/JP-8 Combustor, Isometric with Catalyst Bed at Top (T) and Cross Section of Combustor (B)

The injected fuel was split between the main pintle, located on the centerline of the combustion chamber, and a fuel film cooling injection ring. Each circuit was fed from a different source, allowing the overall MR and fuel film cooling percentage to be independently varied.

Table 1. Nominal Design Conditions for Signature Tailoring Test Hardware

O/F mass mixture ratio	6.0
Chamber pressure, psia	900
Oxidizer	90% H_2O_2
Fuel	JP-8
Overall fuel flow rate, lb_m/s	0.68
Oxidizer flow rate, lb_m/s	4.1
Throat diameter, in.	1.065
Contraction ratio	5.3:1
Nozzle expansion ratio	11:1

The fuel injection system was constructed so as to readily replace both the pintle fuel injector (pintle tip) and the fuel film injector (film ring). Since good performance was achieved during the first tests, the same pintle tip was used for all runs. Three fuel ring designs were fabricated as well, and they were changed during the testing, primarily as a result of ring failure. The water-cooled chamber's liner was designed to butt against the fuel ring. An unforeseen consequence was that the film ring was required to react to the hydraulic load on the liner. Substantial heat would also soak-back into the fuel ring structure after the tests. During certain tests, the load imparted by the water-cooled liner to the hot fuel ring was sufficient to plastically deform the ring. Two of the three fuel rings used are shown in Figure 2. The majority of the tests were run with the swirl injection fuel ring design (SEI00106-2).

The first tests revealed that the throat region of the water-cooled chamber, where the wall was thick, behaved more like a heat sink copper mass. This result limited test duration to about three seconds. Fortunately, the hardware was equipped with a thermocouple embedded in the liner at the throat. This allowed us to adjust the test duration to keep the

temperature of the copper below 1000°F. The liner was re-designed for the second test series with the intention of improving cooling at the throat, and thereby increasing test duration.

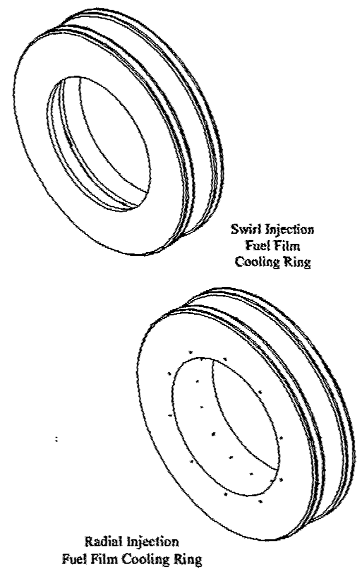

Figure 2. Fuel Film Injector Designs SEI00106-2 (T) and SEI00106-4 (B)

The re-design of the throat cooling circuit thickened the wall in order to enable test of longer duration (Figure 3). A detailed steady state, thermal-structural analysis was completed on the new design to ensure these modifications would operate as desired. The analysis predicted the maximum liner temperature would be 1160°F, which would allow the hardware to run indefinitely.

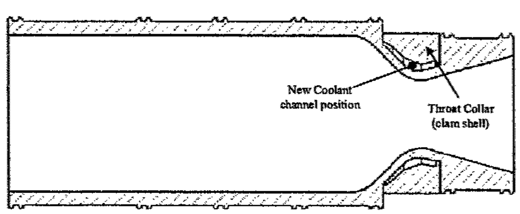

Figure 3. Improved Water-Cooled Liner Design

The new design was tested during the second test series in June 2001. It worked well for the first four tests. All temperature measurements were well within acceptable levels during a five-second run (Test 103). Unfortunately, the hardware was run with insufficient water in the coolant tank during the fifth test (Test 105), destroying the chamber housing, sleeve and nozzle extension.

Test Results

The test matrix varied fuel film cooling percentage, fuel composition, and oxidizer-to-fuel mass MR to determine the effect on engine performance. The hardware was designed to operate at 900 psia chamber pressure, but facility limitations and larger than expected pressure drops through the hot gas duct restricted the operating chamber pressure to around 800 psia during the first test series. The facility problems were solved after the first series, allowing subsequent tests to be run at chamber pressures up to 967 psia. The engine was operated fuel-rich during all tests with the MR ranging between 3.75 and 7.4. Optimum theoretical specific impulse performance for most tested fuels was at a MR near 7.5.

Actual test operating conditions and performance results are summarized in Table 3. Performance measures include specific impulse and two combustion efficiencies – ηC^* and ISP-based ERE. The combustor performed well, with C* efficiencies typically greater than 90%. It is interesting to note that optimum performance of this engine and chamber design requires some amount of film cooling. In test 103, a C* efficiency of over 99% was obtained. However, a similar test with reduced film cooling (test 102) resulted in a reduced C* efficiency of 95%. In this chamber, this effect is the result of the fuel streams emanating from the pintle injector having trouble thoroughly penetrating the hot, high velocity decomposed hydrogen peroxide gas. Consequently, some fuel had to be injected near the combustor wall to obtain good mixture uniformity. As would be expected, very large wall cooling flows also resulted in a decrease in C* efficiency.

Table 2. Fuels Evaluated

JP-8
RP-1
JP-10
Quadricyclane
Turpentine
Toluene
87% JP-8 + 13% Quadricyclane
50% JP-8 + 50% Quadricyclane
85% JP-8 + 15% Toluene
50% JP-8 + 50% Toluene

Table 3. Summary Test Results

Test	Date	Pc (psia)	MR	% film	Fuel Flow (lb_m/s)	Ox Flow (lb_m/s)	Isp vac (lb_f-s/lb_m)	ηC^*	ERE	Fuel
001	5/9/2001	399	-	-	-	4.16	131.86	-	-	none
004	5/11/2001	737	4.39	42.8%	0.82	3.58	248.97	95.1%	94.0%	JP-8
005	5/11/2001	750	3.80	51.5%	0.95	3.60	245.20	96.1%	95.4%	JP-8
006	5/11/2001	750	3.75	52.2%	0.96	3.61	246.18	96.1%	96.0%	JP-8
007	5/11/2001	814	4.22	57.3%	0.93	3.92	248.02	95.9%	94.3%	JP-8
008	5/12/2001	799	5.02	50.0%	0.78	3.94	246.18	94.0%	90.8%	JP-8
011	5/12/2001	829	6.27	43.8%	0.65	4.09	257.17	94.9%	92.2%	JP-10
012	5/14/2001	841	4.28	54.0%	0.92	3.95	253.72	98.3%	96.2%	JP-8
014	5/15/2001	812	4.02	53.6%	0.98	3.94	243.67	94.9%	93.6%	JP-8
020	5/16/2001	808	3.93	54.0%	0.98	3.86	246.45	96.6%	95.2%	JP-8
021	5/16/2001	820	5.25	47.9%	0.78	4.08	251.46	93.2%	92.2%	JP-8
022	5/16/2001	792	6.49	43.0%	0.62	4.03	258.44	92.4%	92.4%	JP-8
023	5/16/2001	786	6.71	42.4%	0.60	4.03	256.64	91.8%	91.5%	JP-8
024	5/16/2001	800	6.54	41.8%	0.62	4.04	260.95	93.1%	93.2%	JP-8
025	5/15/2001	800	6.53	41.9%	0.62	4.03	261.27	93.3%	93.3%	JP-8
026	5/15/2001	799	5.88	41.4%	0.69	4.03	255.23	92.5%	92.2%	JP-8
028	5/16/2001	786	4.40	47.8%	0.87	3.85	250.57	94.3%	94.5%	JP-8
029	5/17/2001	806	4.36	48.1%	0.89	3.86	249.86	96.3%	94.4%	JP-8
030	5/17/2001	803	5.25	46.1%	0.75	3.96	251.93	94.2%	92.3%	JP-8
031	5/17/2001	796	4.90	49.1%	0.80	3.94	250.89	90.7%	89.5%	Turpentine
033	5/17/2001	787	5.64	42.6%	0.69	3.89	259.14	91.7%	89.9%	Quadricyclane
034	5/17/2001	789	4.36	54.3%	0.90	3.94	245.53	89.7%	89.3%	JP-10
038	5/17/2001	783	5.26	45.8%	0.75	3.94	252.57	92.4%	92.6%	JP-8
039	5/17/2001	780	5.24	45.5%	0.75	3.92	252.26	90.8%	90.5%	RP-1
040	5/17/2001	787	6.09	40.3%	0.64	3.89	262.03	93.4%	91.8%	50% JP-8 50% Quadricyclane
041	5/17/2001	776	4.15	49.5%	0.92	3.83	248.10	90.2%	90.7%	JP-10
042	5/17/2001	771	6.06	42.9%	0.66	4.01	249.47	89.4%	88.4%	JP-10
043	5/17/2001	778	4.33	48.9%	0.89	3.85	249.71	93.4%	94.5%	JP-8
102	6/26/2001	677	4.41	17.0%	0.75	3.30	250.06	95.0%	94.3%	JP-8
103	6/26/2001	813	5.35	37.1%	0.73	3.89	261.45	99.3%	99.1%	JP-8
212	8/30/2001	792	5.63	42.8%	0.70	3.91	256.85	94.3%	93.3%	87% JP-8 13% Quadricyclane
405	11/14/2001	910	5.43	64.6%	0.82	4.45	252.27	90.5%	91.5%	JP-8
406	11/14/2001	912	5.27	64.6%	0.85	4.49	249.03	89.0%	90.0%	Toluene
407	11/15/2001	898	5.06	64.6%	0.86	4.35	249.93	90.7%	90.7%	Toluene
411	11/15/2001	967	6.50	40.0%	0.69	4.51	268.04	96.0%	95.2%	JP-8
415	11/16/2001	894	5.86	64.6%	0.76	4.45	250.46	89.1%	89.6%	50% Toluene 50% JP-8
416	11/16/2001	843	5.91	64.6%	0.70	4.15	250.64	90.2%	89.6%	50% Toluene 50% JP-8
417	11/16/2001	845	6.12	64.6%	0.69	4.23	246.76	89.0%	87.8%	15% Toluene 85% JP-8

Table 2 lists the fuels reported in these tests; however, the majority of the tests were run with JP-8, the baseline fuel. As stated, one of the goals of this testing was to evaluate the performance characteristics of different hydrocarbon fuels. Of interest were changes in both the delivered specific impulse (ISP) and combustion efficiencies with varying fuel composition. The theoretical and measured increases in performance over the baseline fuel (JP-8) are compared in Figure 4 for the fuels and fuel blends. Most fuels, unfortunately, were only tested for one firing. The operating condition for each test was intended to produce the same chamber pressure and engine mixture ratio, but facilities issues and uncertainties in fuel densities produced some scatter in the operating conditions. Densities for the different fuels were taken from literature. In the future, it would be better to measure the fuel density of the lot being tested to ensure accuracy.

The operating MR varied from 4.4 to 6.1 during these tests. The measured performance increase for each fuel over JP-8 was determined by comparing alternate fuel measurements to calculated JP-8 performance at the alternate fuel test conditions. The delivered performance for JP-8 at the alternate fuel operating condition was estimated by assuming constant energy release efficiency. The primary metric was an increase in ISP. The graph shows that, in all cases, the theoretical calculation predicted an increase in ISP over JP-8, and the measurements support that trend. The average error between measured and theoretical is 0.1%, or roughly 0.25 seconds; however, there are a couple of fuels that showed much larger errors. This suggests that energy release efficiency remained constant through the testing of the alternate fuels. The 0.1% difference is well within the measurement uncertainty.

Pure quadricyclane demonstrated substantially lower ISP improvements than theory would predict, while the measured ISP improvements of JP-8/quadricyclane blends showed reasonable agreement with theoretical predictions. The significant shortfall below theoretical for the pure quadricyclane was likely the result of lower than expected fuel quality. Quadricyclane naturally decays into norbornadiene, a lower energy C_7H_8 ring compound. The quadricyclane used in these tests had been stored in a fuel bunker for over a year, and the assay of the fuel was not verified before testing began. The quadricyclane was assumed to be pure; however, assays completed after the tests found it to contain roughly 4% impurities. The quadricyclane blends did not show a similar degradation in performance; however, the quadricyclane used in the blends was not taken at the same time as the fuel used in the straight quadricyclane tests. However, both fuel samples were taken from the same barrel of quadricyclane.

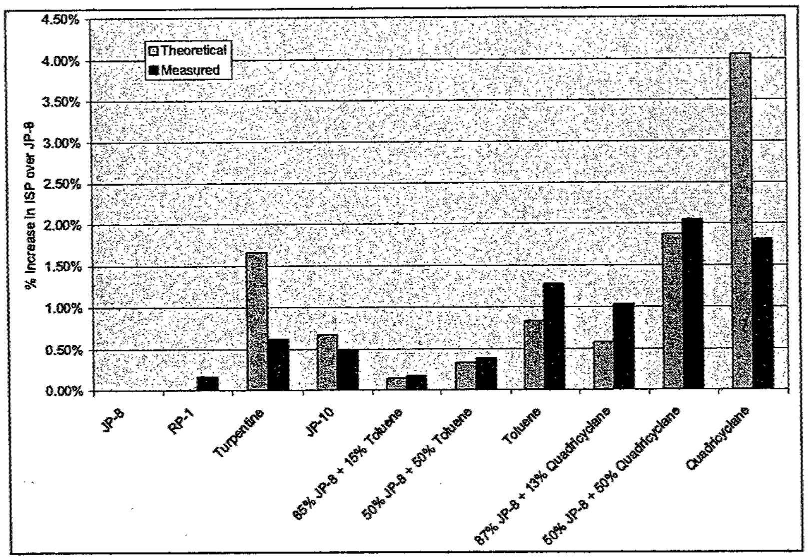

Figure 4. Comparison of Theoretical and Measured Specific Impulse Increase over JP-8 Baseline for Several Fuels

Toluene and toluene/JP-8 blends consistently outperformed predictions, with the largest variation occurring with the neat toluene. This interesting feature may be due to better burning of the toluene ring molecule, or may result from the uncertainty in the cavitating venturi flow calibration (the venturi were never calibrated with toluene).

The turpentine theoretical calculation assumed the turpentine was α-pinene, while the actual turpentine tested was a distillate containing several hydrocarbon molecules. The α-pinene assumptions can easily account for the 1% theoretical over prediction for this test. It is amusing to note that the turpentine, which was purchased from a Kmart™ in Lancaster, California, outperformed RP-1.

The theoretical RP-1 calculation used the same reactants data as JP-8. Consequently, the theoretical calculation for JP-8 and RP-1 are identical. The test data showed a 0.5% (1.25 seconds) improvement in performance with RP-1 over JP-8. This is reasonable since RP-1 is a narrow-distillate in the JP-8 family.

IR Plume Measurements

In order to gain a better understanding of how plume measurements can be used to better monitor engine operation, a spectrometer was used to measure full plume emission spectral intensities from the engine exhaust plume. Variation in engine operating performance and conditions should be readily identifiable through easily measured differences in the exhaust species and temperatures. Furthermore, use of a spectrometer does not require modifications to test hardware for the presence of instrumentation, which can be a difficulty in large-scale hardware.

The plume intensity readings were found to be very sensitive to engine operation; therefore, they show potential as a combustion diagnostic tool. This section briefly describes the data taken, and then shows examples of the plumes IR signature to engine operation.

A Bomem MR200 Fourier Transform Infrared (FTIR) spectroradiometer, supplied by NGC, collected plume data during the first two test series. The FTIR included two detectors, indium arsenide and a mercury cadmium telluride (MCT), permitting simultaneously data collection over an included spectral range of 0.8 to 15 μm. The spectrometer was located approximately 36 meters from the engine with approximately a 90° aspect angle with respect to the plume centerline (i.e., perpendicular). Data was collected at 34 Hz with a 4 cm^{-1} spectral resolution. The instrument was calibrated with a collimated blackbody source at two temperatures. The NGC spectrometer was primarily used to gauge the relative changes in intensity with engine operating conditions. A similar FTIR, provided by the AFRL plumes group, was used for the last two test series. It also used two detectors simultaneously, an MCT and an indium antimonite (InSb). The MCT detector had a spectral range of approximately 2 to 18 μm while the InSb

detector range was from 1 to 6 µm. The AFRL spectrometer was located approximately 43.6 meters from the engine, also with a 90° aspect angle. The full-width half-max (FWHM) field of view was approximately 2.5 meters with the AFRL spectrometer. Due to the configuration and location differences between the two spectrometers, the data are not directly comparable.

The spectrometer proved to be quite sensitive to engine operation. A general idea of how well the engine ran was observable in the intensity fluctuations before it could be ascertained from the conventional test data (e.g., pressures, temperatures, flow rates). Not only was the FTIR quick-look data reduction faster than the Cyber system in the control room, but small changes in engine operation were found to produce easily observable variations in IR signature. A full correlation of the test results has not been conducted; however, an illustrative sample is provided to support this claim. The IR intensity and combustion chamber pressure are plotted on similar scales in Figure 5 for Test 042. The strong correlation between IR intensity and chamber pressure variations is clear. In fact, the IR measurements were found to be at least twice as sensitive as standard pressure measurements to changes in the combustion process.

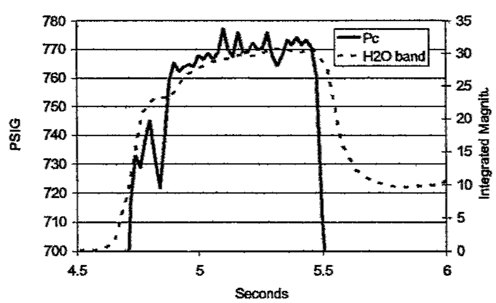

Figure 5. Chamber Pressure (Pc) and Integrated Band Intensity of Test 042

The IR results typically showed high sensitivity to subtle changes in the combustion process, but not all peaks and valleys could be correlated to changes in engine operation. Sometimes there appeared to be a time lag between variations in the pressure and IR traces (Figure 6), but further investigation often showed that operating conditions other than chamber pressure were affecting the IR signature. Traces for the same IR bands are shown with the oxidizer injection pressure drop in Figure 7; the variations align well with the oxidizer injector pressure drop, suggesting that the signature variation is driven by oxidizer flow variations to the chamber. Subsequent investigation of Test 008 indicated that the oxidizer tank pressure varied as a result of relief valve openings. The 20 psi variation in injector pressure drop produced a 50% change in these two IR measurements.

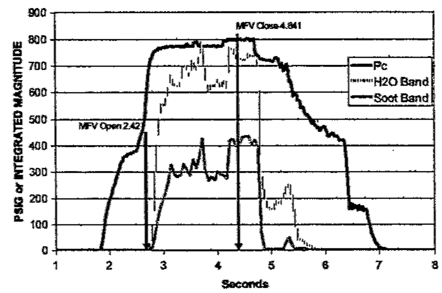

Figure 6. Chamber Pressure (Pc) and Two IR Bands for Test 008

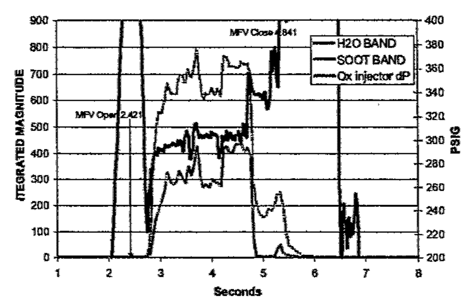

Figure 7. Ox Injection Pressure Drop and Two IR Bands for Test 008

The sensitivity of the infrared radiation measurement suggests that this type of diagnostic could be very important to combustor testing and operation. One significant advantage of plume radiation measurements is that they can be separated easily from the test article and the facility, and are often easily transported. This, combined with their high sensitivity to operating condition changes, suggests they could be a very important future diagnostic tool.

Conclusions

Testing of a 1300 pound thrust hydrogen peroxide hydrocarbon engine was performed at the AFRL propulsion directorate at Edwards AFB, California.

Ten different hydrocarbon fuels, including several fuel blends, were evaluated. Operating condition variations included MR and fuel film cooling percentage. Overall, performance data showed good agreement with theoretical ISP benefits of the various fuels tested. However, two of the fuels, neat quadricyclane and toluene, showed noticeable deviation from the theoretically predicted performance increase.

Examples are also presented showing the strong correlation between plume infrared radiation and engine operating condition variation. The high sensitivity of the infrared plume signature to combustion variations identifies a class of diagnostic tools that could be important in future engine test and development programs.